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THE SOLAR CONSTANT

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(Manuscript received 1 March 1954)

ABSTRACT

The value of the solar constant indicated by 30 years of observation by the Smithsonian Institution is revised in the light of the scale correction announced in 1952 and new solar spectral-irradiance data for outside the earth's atmosphere obtained by the Naval Research Laboratory. The ultraviolet and infrared corrections applied by the Smithsonian Institution in solar-constant determinations are examined and re-evaluated. The accuracy of their measurement of total irradiance in the spectral range 0.346 to 2.4 microns is in general supported, only a 0.3 per cent increase being indicated owing to revision of a correction applied in reaching their value. The corrections for radiation outside this spectral range are found to be larger than those used by the Smithsonian Institution. The new value of the solar constant is 2.00 calories per square centimeter per minute, with a probable error of two percent, and the solar-illuminance constant is 13.67 lumens per square centimeter (12,700 foot-candles).

1. Introduction

The solar constant is the rate at which energy is received upon a unit surface, perpendicular to the sun's direction, in free space at the earth's mean distance from the sun. It is generally expressed in calories per square centimeter per minute, and in these units has usually been considered to lie in the range 1.89 to 1.95. Recently, the ultraviolet end of the solar spectrum from 0.22 to 0.34 μ has been measured by Johnson *et al* [1] with rocket-borne spectrographs. From the visible region down to 0.30 μ, new data were available from measurements made by Dunkelman and Scolnik [2]. These results made it possible to determine directly the ultraviolet correction to the solar constant, and served as a stimulus to review the entire question of the value of the solar constant and the spectrum of the sun. The resulting best value for the solar constant is 2.00 cal cm^{-2} min^{-1}, with a probable error of ± 2 per cent.

2. The measurements of the Smithsonian Institution

The most extensive investigation of the solar constant has been made by Abbot, Fowle, Aldrich, and Hoover of the Astrophysical Observatory of the Smithsonian Institution [3; 4; 5; 6; 7]. Their primary purpose has been to detect variation in the solar constant, and their interest in its absolute value has always been secondary. Nevertheless, the data of the Smithsonian Institution provide the best source of information on the absolute value of the solar constant, and their value is the one most frequently used and quoted. However, there has been, for a number of years, [illegible] over the scale in which their data are presented, and frequently the data have been used incorrectly.

The determination of the solar constant by the Smithsonian Institution [4] follows the classical method of Langley. Several solar spectral-irradiance curves are obtained on absolute scales for different solar altitudes, or air masses (approximately the secant of the sun's zenith angle), during a forenoon or afternoon. The irradiance values for a selected wavelength are fitted to Bouguer's law, and the corresponding zero air-mass irradiance value is determined by extrapolation. Similar extrapolations are made for a number of wavelengths and provide enough points to draw the zero air-mass solar spectral-irradiance curve. The energy lying under the zero air-mass curve, corrected for the ultraviolet and infrared radiation not included in the observations and referred to mean solar distance, is the solar-constant value resulting from the observations of the particular forenoon or afternoon.

Since the steps involved in obtaining the data and applying the corrections are rather difficult to follow, the observing procedures of the Smithsonian Institution are shown in the form of a block diagram in fig. 1; this is intended to serve as an aid in following through the reconsideration of the various steps and corrections, which forms the main part of the present article.

The solar spectral-irradiance curves are obtained with a recording spectrobolometer, consisting of a large spectrometer with a bolometer receiver [5]. The absolute energy scale, however, is established by reference to a measurement of total radiation made at the same time with a pyrheliometer. This was found necessary, because the sensitivity of the bolometer is subject to some drift between the recording of one spectrobologram and the next. The area under each spectrobologram is normalized, to make it equal to the energy indicated by the pyrheliometer. Thus, the pyrheliometer is the standard instrument upon which the scale of the solar-constant measurements is based.

A series of corrections is required, owing to the fact that the spectral range covered by the spectrobolometer is only from 0.346 to 2.4 μ, whereas the pyrheliometer is affected by all the solar radiation transmitted through the atmosphere. Consequently, corrections for the ultraviolet and infrared not recorded by the spectrobolometer must be applied before the spectrobolograms are normalized to the pyrheliometer readings. These corrections, which we will refer to as the "ultraviolet and infrared *spectrobologram corrections*," have been determined by the Smithsonian Institution [6; 8]. The accuracy of the scale for all the spectral-irradiance curves depends upon the accuracy of these corrections. These corrections depend upon the solar altitude and the quantity of water vapor and state of haze over the path to the sun. They involve the measurement of the small amounts of radiation reaching the earth's surface at the extreme ends of the solar spectrum, and are applied as additions to the areas under the spectrobolograms

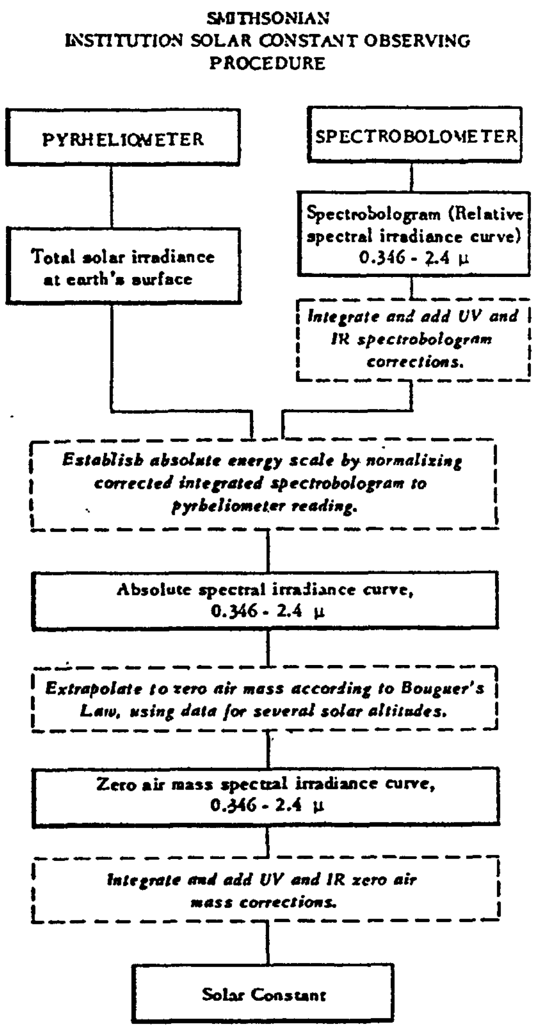

FIG. 1. Flow chart of Smithsonian Institution solar-constant observing procedure.

before normalization to the pyrheliometer readings. The spectrobolograms are thus placed on an absolute energy scale and become spectral-irradiance curves covering the range 0.346 to 2.4 μ. Finally, the extrapolation to zero air mass of these curves, wavelength by wavelength, will yield a zero air-mass solar spectral-irradiance curve on an absolute energy scale and covering the spectral range 0.346 to 2.4 μ.

Since the solar constant is the energy in the entire solar spectrum for all wavelengths from zero to infinity, corrections must be added to the areas under the zero air-mass spectral-irradiance curves to take into account the energy outside the range 0.346 to 2.4 μ of the spectrobolometer observations. These corrections, to a great extent comprising wavelengths that never reach the ground, we shall refer to as the "ultraviolet and infrared *zero air-mass corrections*." Values of these corrections have been estimated by the Smithsonian Institution [6; 8]; however, a clear distinction between the different natures of the *spectrobologram* and *zero air-mass* types of correction was not made.

The ultraviolet and infrared *zero air-mass correction* cannot be accurately determined from measurements made at the ground, because most of the energy involved does not reach the ground. In thinking of the corrections, it is convenient to separate them into two parts; the first covers wavelengths which, although attenuated, do reach the earth's surface, and can be measured from the ground; the second includes all wavelengths which are entirely absorbed in the atmosphere, and cannot possibly be determined from ground measurements. In the ultraviolet, the spectral region 0.29 to 0.346 μ can, in general, be observed from the earth's surface; but owing to the very great atmospheric attenuation for the shorter wavelengths, the accuracy with which the extrapolation to zero air mass can be made is apt to be low. For wavelengths shorter than 0.29 μ, ground measurements are not possible at all, since ozone absorbs all the radiation even when the sun is near the zenith; until the rocket measurements became available, this part of the ultraviolet *zero air-mass correction* could only be estimated. The situation with the infrared *zero air-mass correction* is somewhat similar.

Inaccuracies in calibration of the equipment, of a nature such as to affect the shape of the spectrobolograms, have an effect upon the solar constant which is not necessarily negligible; this effect is introduced in the extrapolation to zero air mass, and is due to the atmospheric attenuation being much greater for short wavelengths than for long. For example, suppose that the spectrobolograms are too low in the infrared; after normalization to the pyrheliometer readings, the curves become raised as a whole by enough to make up the deficiency in the infrared. This makes the visible and ultraviolet portions of the normalized spectrobols a little too high, while the infrared portions n a little low. Although the total areas under rmalized spectrobolograms are correct, an error roduced upon extrapolation to zero air mass, because the atmospheric attenuation for the ultraviolet and visible is greater than that for the infrared. In the example given, the infrared deficiency would not be increased appreciably upon extrapolation to zero air mass. However, the ultraviolet and visible excess energy, which just compensated for the infrared deficiency in the individual normalized spectrobolograms, would be magnified upon extrapolation to zero air mass because of the lower atmospheric transmission coefficient in this spectral region, and would then overcompensate the infrared deficiency; as a result, the integrated energy under the zero air-mass curve would be a little too high. Thus, a magnification of the ultraviolet and visible errors relative to the infrared error is produced by the difference in the atmospheric transmission coefficients appropriate to these spectral regions. The Smithsonian Institution does not claim great accuracy for the shape of the spectrobolograms, since it spent no great effort in making the curves any more accurate than required for its principal purpose, which was to determine variations e solar constant. It states [9] that some uncer- y remains in the spectrometer transmission cor- ns, which must be applied in obtaining the spec- ograms; any such uncertainty is carried directly over to the spectral-irradiance curves.

The Smithsonian Institution has also used a "short method" of observation, which does not involve the use of the spectrobolometer. However, the determination of the absolute value of the solar constant rests upon the "long method" described above, and the "short method" simply provides a means of accumulating solar-constant data more rapidly, but on the scale determined by the "long method."

The mean of the solar-constant determinations made over a 30-yr period by the Smithsonian Institution [10] was reported in 1952 to be 1.946 cal cm^{-2} min^{-1}, in the scale of pyrheliometry "in actual use" over this period. At the same time, this scale was stated to yield results which are 0.6 per cent too high.[1] Therefore, the mean value of the solar constant at present upheld by the Smithsonian Institution is 1.934 cal cm^{-2} min^{-1}.

The basic quantity actually measured by the Smithsonian Institution, however, is the energy between 0.346 and 2.4 μ. The value for this portion of the solar constant can be deduced by subtracting the ultraviolet and infrared *zero air-mass corrections* from the value 1.934 cal cm^{-2} min^{-1}. It can be shown, from its definitions of the corrections and its spectral intensity distribution, that the values are 0.061 and 0.038 cal cm^{-2} min^{-1}, respectively, for the ultraviolet and infrared energy that lies outside the spectral range covered by the spectrobolometer. Therefore, the Smithsonian Institution data indicate that the solar irradiance outside the earth's atmosphere and at mean solar distance within the spectral range 0.346 to 2.4 μ is 1.835 cal cm^{-2} min^{-1}.

3. The new spectral irradiance curve

New zero air-mass solar spectral-irradiance data, covering the wavelength range 0.22 to 0.60 μ, have recently been obtained at the Naval Research Laboratory. The values from 0.22 to 0.34 μ were obtained by Johnson *et al* [1] by direct measurements from high-altitude rockets; they were considered to be accurate within ± 5 per cent on a relative scale of energy, but the absolute energy scale was subject to greater error. The spectral range from 0.30 to 0.68 μ was covered by Dunkelman and Scolnik [2], who made measurements from Mount Lemmon, Arizona, and extrapolated to zero air mass. Data were obtained with much greater spectral resolution than in most previous work, and the use of a double monochromator insured greater freedom from stray light than could be attained with single dispersion, as used by the Smithsonian Institution. The curve was presented on an absolute scale, with an accuracy of ± 10 per cent. Regarded as a relative distribution of energy, the curve was considered more accurate, with a probable error of ± 3 per cent. It seemed probable that the absolute energy scale of both sets of data could be determined most accurately by comparison with the Smithsonian observations.

After study of all the available data, it was concluded that the most accurate zero air-mass solar spectral-irradiance curve on a relative energy scale would be obtained by use of the Naval Research Laboratory data up to 0.60 μ and Moon's [14] data to longer wavelengths. The latter are based mainly upon the Smithsonian observations and are the data given in the 1952 (9th) edition of the *Smithsonian physical tables*. There have been suggestions that this curve is too low in the infrared. However, since some recent observations of Peyturaux [15] agree very well with the curve as Moon drew it, the curve will be accepted as the best infrared data available at this time. The most satisfactory wavelength at which to join Dunkelman and Scolnik's data to Moon's ap-

[1] The scale of pyrheliometry "in actual use" by the Smithsonian Institution in its observations is now stated to be the scale in which all its solar-constant results have been presented. Although it has been thought for many years that the Smithsonian results presented in terms of the "scale of 1913," the Smithsonian ution [10] in 1952 says that this is not so, and that its s must be increased by 1.8 per cent to be in terms of the scale of 1913." However, as was stated by the Smithsonian tion [11; 12; 13] once in 1934 and twice in 1948, the 1913 gives results which are 2.4 per cent too high. There- ne scale "in actual use" and the presented data require a correction of 0.6 per cent downward. If this is done, the results are given in terms of the "scale of 1932," which is considered to be correct.

peared to be 0.60 μ, and it was necessary to raise their data by 6 per cent above the values indicated by their absolute scale to make the match. The rocket data, in turn, were adjusted to the curve of Dunkelman and Scolnik at 0.318 μ. To eliminate the detailed Fraunhofer structure, the Naval Research Laboratory data were averaged over 100-Å intervals.

In fig. 2, the resulting composite curve is shown. The solid curve represents the rocket data for wavelengths shorter than 0.318 μ, and Dunkelman and Scolnik's data for longer wavelengths. The dashed curve, following Moon's data, is to be used beyond 0.60 μ; the portion below 0.60 μ is included merely for comparison. Although the absolute energy scale is given, for the moment the curve must be regarded as relative only; the determination of the absolute scale is described below.

4. Revision of the ultraviolet corrections

The solid curve of fig. 2, with the energy scale considered as only relative, can now be used to compute the ultraviolet *spectrobologram corrections*. These are defined by the Smithsonian Institution as the solar irradiance at the earth's surface in the spectral region below 0.346 μ, expressed as a percentage of the total solar irradiance at the ground for the spectral range 0.346 to 0.704 μ. They are functions of the air mass and of the prevailing atmospheric clarity. The wavelength 0.704 μ, chosen arbitrarily by the Smithsonian Institution, divides approximately in half the solar energy between 0.346 and 2.4 μ outside the earth's atmosphere.

Values of the corrections were calculated for the atmosphere above Montezuma, Chile, for a range of air masses from 1 to 5, with the assumption of Rayleigh attenuation, including the polarization defect, and 2.25 mm of ozone. The result is shown in fig. 3, along with the correction curves used by the Smithsonian Institution [6; 8] for three different conditions of atmospheric clarity, also for Montezuma. For an atmosphere of maximum clarity, it can be seen that the Smithsonian correction for air mass one is about 0.4 percentage units too large; for air mass three, the correction is nearly perfect, and for larger air masses the corrections are slightly too small.

The result of the small discrepancy between the present ultraviolet correction curve and that of the Smithsonian Institution is to increase the solar zerc air-mass irradiance in the interval 0.346 to 2.4 μ by about 0.3 per cent. The reasoning follows. For air mass one, the Smithsonian Institution overestimates the ultraviolet *spectrobologram correction* by 0.4 percentage units. Therefore, its normalized spectrobolograms for unit air mass are too low by about 0.4 per cent of the energy between 0.346 and 0.704 μ. For air mass two, the error is about half this amount, and for air mass three, there is no error. For larger air masses the normalized spectrobolograms are a little too high In the process of extrapolation to zero air mass, these errors in the normalized spectrobolograms become magnified to a deficiency of 0.7 per cent of the energy between 0.346 and 0.704 μ. Since the total energy in this spectral range, for zero air mass, is 0.900 cal cm^{-} min^{-1}, the error is $0.900 \times 0.007 = 0.006$ cal cm^{-} min^{-1}. Thus, examination of the Smithsonian ultraviolet *spectrobologram corrections* indicates that the value of the zero air-mass solar irradiance between 0.346 and 2.4 μ should be increased from 1.835 to 1.841 cal cm^{-2} min^{-1}.

The normally present fluctuations in the amount of ozone do not produce important changes in the ultraviolet *spectrobologram corrections*, and can be neglected The curve in fig. 3 was calculated for 2.25 mm of ozone. Similar curves, calculated for 1.50 and 3.00 mm of ozone, do not differ from the curve shown for 2.25 mm by more than 0.2 percentage units. According to Dobson's [16] data, the ozone amount at Montezuma does not change much through the course of the year, and is generally near 2.25 mm.

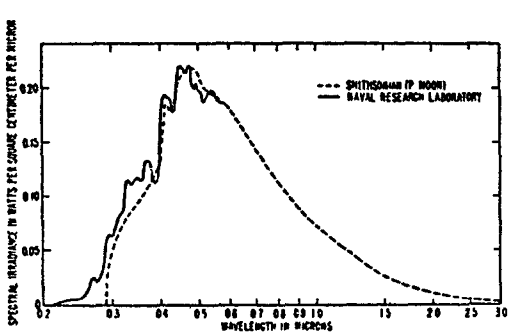

FIG. 2. Solar spectral-irradiance curve outside earth's atmosphere, corrected to mean solar distance.

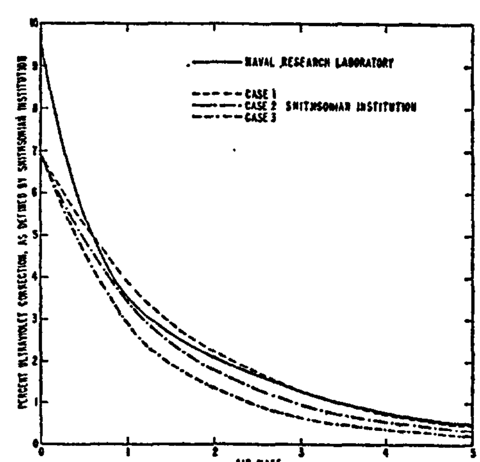

FIG. 3. Ultraviolet corrections, defined by Smithsonian Institution as energy for wavelengths shorter than 0.346 μ expressed as percentage of energy in wavelength region 0.346 to 0.704 μ. Values for air mass one and greater are *spectrobologram corrections*; values for air mass zero are *zero air-mass corrections*. Three cases shown for Smithsonian Institution are for three different conditions of atmospheric clarity, case 1 being for highest atmospheric clarity.

The ultraviolet *zero air-mass correction* was calculated from the Naval Research Laboratory curve of fig. 2, and is also shown in fig. 3. The result is that the zero air-mass solar irradiance for wavelengths shorter than 0.346 μ is 9.5 per cent of the zero air-mass solar irradiance in the spectral region 0.346 to 0.704 μ. The value estimated by the Smithsonian Institution, also shown in fig. 3, is 6.88 per cent, and is appreciably less than the present value. Use of our value for the ultraviolet *zero air-mass correction* has the effect of increasing the solar constant by (9.5–6.88) per cent, or 2.6 per cent, of the zero air-mass solar irradiance in the spectral interval 0.346 to 0.704 μ. This revision results in an addition of 0.024 cal cm^{-2} min^{-1} to the solar constant.

5. Revision of the infrared corrections

New values of the infrared corrections were computed on the basis of the solar curve shown in fig. 2. From 0.704 to 1.2 μ, this curve is the mean proposed by Moon after a study of the existing data. From 1.2 to 2.4 μ, the curve is drawn as a 6000K gray-body because, according to Moon, this fits all the data in this range better than any other curve. Beyond 2.4 μ, no complete spectrum has been obtained outside the atmosphere, but the spectrum has been studied by [illegible] [17; 18] at the ground through a number of atmospheric windows. The portions of the spectrum observed fit a 6000K gray-body curve fairly well, and since Fraunhofer absorption is comparatively weak in the infrared it appears safe to interpolate between the windows and to assume that the solar spectrum outside the atmosphere from 2.4 to at least 14 μ is similar to that of a 6000K gray-body. Actually, it is necessary to consider the solar spectral-irradiance curve out to 6 or 8 μ only, since very little energy is associated with wavelengths longer than this.

The infrared *spectrobologram corrections* were regarded by the Smithsonian Institution as functions of water-vapor absorption only, which was justifiable because of the smallness of the attenuation due to Rayleigh scattering in this spectral region. The corrections were defined as the ratio of the solar irradiance beyond 2.4 μ to the irradiance from 0.704 to 2.4 μ—both measured at the ground, but smoothed over the atmospheric absorption bands present in the range 0.704 to 2.4 μ. They were determined from direct spectrobolometric measurements, made with a rock-salt prism over the range 0.704 to 10 μ and covering the range 2.5 to 5.4 cm of precipitable water vapor. An actual calculation of the infrared *spectrobologram corrections*, starting with the solar spectral intensity distribution and the absorption spectra of the atmosphere, is not simple, because of the complicated nature of water-vapor absorption, and was not attempted. Instead, use was made of the work of Yates [19], who calculated as a function of wavelength the amount of energy from a 6000K black-body source penetrating a 2000-yard horizontal path containing 0.9 to 3.6 cm of precipitable water vapor. This calculation was based upon extrapolations of recent laboratory measurements of the spectral attenuation of air containing known amounts of water vapor and carbon dioxide, and is not a close parallel to the optical path to the sun through the atmosphere above Montezuma. However, the agreement is surprisingly good.

In fig. 4 are shown the Smithsonian [6; 8] correction curve and the result from Yates' data. It can be seen that the curves are in satisfactory agreement near 3 cm of precipitable water, where the data overlap. The difference in slope between the two curves may be due to the great differences in conditions such as pressure, temperature and spectral resolution, or even due to the fact that an extrapolation of the infrared absorption data was involved in Yates' calculations for these amounts of water vapor. The writer is therefore prepared to accept the Smithsonian infrared *spectrobologram corrections* as the best values now available, and cannot suggest that any error was introduced by these corrections into the Smithsonian measurement of the zero air-mass solar irradiance between 0.346 and 2.4 μ.

To obtain the infrared *zero air-mass correction*, the Smithsonian Institution extrapolated its observed infrared *spectrobologram corrections* to zero air mass in the simple fashion shown in fig. 4. The solid curve, based upon Yates' data, shows that the manner in which this was done was not correct. The Smithsonian curve should have turned sharply upward somewhere below 1 cm of precipitable water vapor. In adopting the curve shown in fig. 4, the Smithsonian Institution failed to recognize the great amount of absorption due to small amounts of water vapor, especially near 2.5 μ. For the Smithsonian value of the infrared *zero air-*

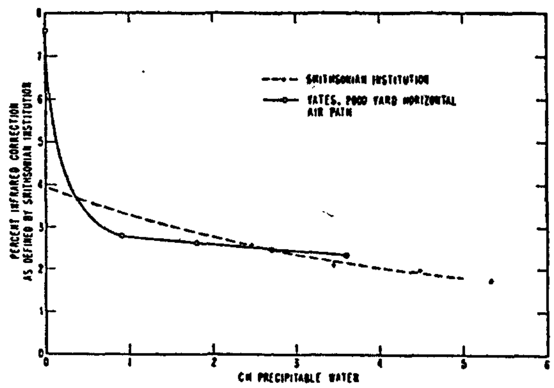

FIG. 4. Infrared corrections, defined by Smithsonian Institution as energy for wavelengths longer than 2.4 μ, expressed as percentage of energy in wavelength region 0.704 to 2.4 μ with atmospheric absorption bands smoothed over. Values for zero water vapor are *zero air-mass corrections*, and values for amounts of water vapor other than zero are *spectrobologram corrections*. Curve bearing Yates' name is adapted from his calculation of transmission of 6000K black-body radiation through horizontal atmosphere, based upon experimental data.

mass correction to be correct, the zero air-mass spectral-irradiance curve would have to fall sharply below the 6000K gray-body curve shortly beyond 2.4 μ. As it is well established that the sun resembles a 6000K gray-body in this region, it is clear that the Smithsonian infrared *zero air-mass correction* is too small.

The infrared *zero air-mass correction* has been computed from the solar energy distribution shown in fig. 2, by calculating the zero air-mass solar irradiance beyond 2.4 μ, and expressing it as percentage of the energy between 0.704 and 2.4 μ. The resulting value is 8.1 per cent, slightly higher than the value of 7.6 per cent shown in fig. 4 and appropriate to a 6000K gray-body, which lies a little above the actual solar curve below 1.2 μ. This is to be compared with the value 3.95 per cent used by the Smithsonian Institution, and acts to increase the solar constant by (8.1–3.95) per cent of the zero air-mass solar irradiance between 0.704 and 2.4 μ, or 0.038 cal cm^{-2} min^{-1}.

6. The absolute energy scale

It is now possible to assign to the zero air-mass spectral-irradiance curve, shown in fig. 2, an absolute scale based upon the work of the Smithsonian Institution. This is considered to be the most accurate determination of the scale, and is used instead of the direct determinations of the absolute energy scale of the ultraviolet data obtained from rockets and from the earth's surface. Normalization is made to the revised value for the zero air-mass solar irradiance in the spectral range 0.346 to 2.4 μ. As shown earlier, the Smithsonian value, 1.835 cal cm^{-2} min^{-1}, for the energy in this region should be increased by 0.006 cal cm^{-2} min^{-1} in accordance with our revision of the ultraviolet *spectrobologram corrections*, but no change in the infrared *spectrobologram corrections* is indicated. The result is 1.841 cal cm^{-2} min^{-1}. The scale shown in fig. 2 applies to the curve as normalized to this value. It is noted that the Smithsonian *zero air-mass corrections* are not in any way involved in fixing this scale.

The energy scale thus established required increasing Moon's data by 2.8 per cent. Dunkelman and Scolnik's results, which had already been increased by 6 per cent to match Moon's at 0.60 μ, were thus raised by 9.0 per cent in all, but remain within the 10 per cent accuracy claimed. In the case of the rocket spectra, an attempt was made by Johnson *et al* [1] to establish an absolute scale. The best value obtained at 0.283 μ was 0.0296 watt cm^{-2} μ^{-1}, and is to be compared with 0.0281 watt cm^{-2} μ^{-1} as read from the normalized curve of fig. 2; the agreement is within about 5 per cent, and is well within experimental error.

The data from which fig. 2 is plotted are given in table 1. The absolute solar spectral-irradiance values for air mass zero, at mean solar distance, are given in the second column. The spectrum below 0.60 μ is presented in more detail in the original papers [1; 2], and in terms of the scale established here. The third column of table 1 gives the percentage of the total solar irradiance between wavelengths 0 and λ; the percentage from λ to infinity is obtained, obviously, by subtraction from 100. These data were determined by integration of the curve in fig. 1. They are particularly useful for obtaining quickly the total solar irradiance within a given spectral band. Thus, 1.23 per cent of the total solar irradiance lies below 0.3 μ, and 0.712 μ is the wavelength dividing the solar spectrum into equal halves.

TABLE 1. SOLAR SPECTRAL IRRADIANCE DATA

Wavelength λ is in microns, the mean zero air mass spectral-irradiance H_λ is in watts cm^{-2} micron^{-1}, and P_λ is the percentage of the solar constant associated with wavelengths shorter than wavelength λ.

λ	H_λ	P_λ	λ	H_λ	P_λ	λ	H_λ	P_λ	λ	H_λ	P_λ	λ	H_λ	P_λ
0.22	0.0030	0.02	0.36	0.116	5.47	0.50	0.198	23.5	0.68	0.151	46.7	2.6	0.00445	96.90
0.225	0.0042	0.03	0.365	0.129	5.89	0.505	0.197	24.2	0.69	0.148	47.8	2.7	0.00390	97.21
0.23	0.0052	0.05	0.37	0.133	6.36	0.51	0.196	24.9	0.70	0.144	48.8	2.8	0.00343	97.47
0.235	0.0054	0.07	0.375	0.132	6.84	0.515	0.189	25.6	0.71	0.141	49.8	2.9	0.00303	97.72
0.24	0.0058	0.09	0.38	0.123	7.29	0.52	0.187	26.3	0.72	0.137	50.8	3.0	0.00268	97.90
0.245	0.0064	0.11	0.385	0.115	7.72	0.525	0.192	26.9	0.73	0.134	51.8	3.1	0.00230	98.08
0.25	0.0064	0.13	0.39	0.112	8.13	0.53	0.195	27.6	0.74	0.130	52.7	3.2	0.00214	98.24
0.255	0.010	0.16	0.395	0.120	8.54	0.535	0.197	28.3	0.75	0.127	53.7	3.3	0.00191	98.39
0.26	0.013	0.20	0.40	0.154	9.03	0.54	0.198	29.0	0.80	0.1127	57.9	3.4	0.00171	98.52
0.265	0.020	0.27	0.405	0.188	9.65	0.545	0.198	29.8	0.85	0.1003	61.7	3.5	0.00153	98.63
0.27	0.025	0.34	0.41	0.194	10.3	0.55	0.195	30.5	0.90	0.895	65.1	3.6	0.00139	98.74
0.275	0.022	0.43	0.415	0.192	11.0	0.555	0.192	31.2	0.95	0.0803	68.1	3.7	0.00125	98.83
0.28	0.024	0.51	0.42	0.192	11.7	0.56	0.190	31.8	1.0	0.0725	70.9	3.8	0.00114	98.91
0.285	0.034	0.62	0.425	0.189	12.4	0.565	0.189	32.5	1.1	0.0606	75.7	3.9	0.00103	98.99
0.29	0.052	0.77	0.43	0.178	13.0	0.57	0.187	33.2	1.2	0.0501	79.6	4.0	0.00095	99.05
0.295	0.063	0.98	0.435	0.182	13.7	0.575	0.187	33.9	1.3	0.0406	82.9	4.1	0.00087	99.13
0.30	0.061	1.23	0.44	0.203	14.4	0.58	0.187	34.5	1.4	0.0328	85.5	4.2	0.00080	99.18
0.305	0.067	1.43	0.445	0.215	15.1	0.585	0.185	35.2	1.5	0.0267	87.6	4.3	0.00073	99.23
0.31	0.076	1.69	0.45	0.220	15.9	0.59	0.184	35.9	1.6	0.0220	89.4	4.4	0.00067	99.29
0.315	0.082	1.97	0.455	0.219	16.7	0.595	0.183	36.5	1.7	0.0182	90.83	4.5	0.00061	99.33
0.32	0.085	2.26	0.46	0.216	17.5	0.60	0.181	37.2	1.8	0.0152	92.03	4.6	0.00056	99.38
0.325	0.102	2.60	0.465	0.215	18.2	0.61	0.177	38.4	1.9	0.01274	93.02	4.7	0.00051	99.41
0.33	0.115	3.02	0.47	0.217	19.0	0.62	0.174	39.7	2.0	0.01079	93.87	4.8	0.00048	99.45
0.335	0.111	3.40	0.475	0.220	19.8	0.63	0.170	40.9	2.1	0.00917	94.58	4.9	0.00044	99.48
0.34	0.111	3.80	0.48	0.216	20.6	0.64	0.166	42.1	2.2	0.00785	95.20	5.0	0.00042	99.51
0.345	0.117	4.21	0.485	0.203	21.3	0.65	0.162	43.3	2.3	0.00676	95.71	6.0	0.00021	99.74
0.35	0.118	4.63	0.49	0.199	22.0	0.66	0.159	44.5	2.4	0.00585	96.18	7.0	0.00012	99.86
0.355	0.116	5.04	0.495	0.204	22.8	0.67	0.155	45.6	2.5	0.00509	96.57			

7. The revised solar constant

A new value of the solar constant can now be computed. Two alternative ways are available, which appear to be different in nature, but actually are essentially the same. One can either integrate under the curve of fig. 2, now that the absolute scale is established, or one can evaluate the revised *zero air-mass corrections* and add them to the revised zero air-mass energy between 0.346 and 2.4 μ. In either case, the result is 0.1396 watt/cm^2, or 2.002 cal cm^{-2} min^{-1}.

The actual values of the revised *zero air-mass corrections* for the spectrum below 0.346 and above 2.4 μ are computed as follows. As discussed previously, the ultraviolet *zero air-mass correction* is 9.5 per cent of the zero air-mass solar irradiance between 0.346 and 0.704 μ. The latter value, from integration of the curve of fig. 2, is 0.900 cal cm^{-2} min^{-1}; hence, the value of the correction is 0.085 cal cm^{-2} min^{-1} and may be compared with the value 0.061 cal cm^{-2} min^{-1} used by the Smithsonian Institution. Similarly, the infrared zero air-mass correction is 8.1 per cent of the zero air-mass solar irradiance between 0.704 and 2.4 μ, which is 0.941 cal cm^{-2} min^{-1}. The correction thus becomes 0.076 cal cm^{-2} min^{-1}, and is twice the value of 0.038 cal cm^{-2} min^{-1} used by the Smithsonian Institution. The solar constant is given by $1.841 + 0.085 + 0.076 = 2.002$ cal cm^{-2} min^{-1}, in agreement with the direct integration.

The solar-illuminance constant is obtained by multiplying the curve of fig. 2 by the standard luminosity curve of the International Commission on Illumination. Integrating and using 680 lumens per watt as the reciprocal of the mechanical equivalent of light, we find the resultant value for the solar-illuminance constant to be 13.67 lumen cm^{-2}, or 12,700 foot-candles.

The spectral-irradiance curve beyond 1.2 μ was described as being the same as that for a 6000K graybody. Now that the absolute scale has been determined, the degree of grayness or the emissivity of the sun can be determined for this spectral region, and is 0.990. Thus, the solar curve falls 1.0 per cent below a 6000K black-body curve, and the sun has a brightness temperature of about 5970K in this spectral region. Other portions of the solar spectral-irradiance curve fall much farther below the 6000K black-body curve. With the spectral resolution presented in fig. 2, only at the peak of the solar spectrum near 4500Å does the brightness temperature exceed 6000K. However, at high resolution, many narrow spectral bands in the near ultraviolet and visible portion of the spectrum are found where the brightness temperature exceeds 6000K.

8. Discussion of errors

The shape of the ultraviolet and visible portion of the solar spectral-irradiance curve is considered now to be established with good accuracy. In the infrared, however, a preliminary note by Gates *et al* [20] suggests that a change of some sort from the data of Moon may eventually be established. Since Gates *et al*'s data are only preliminary in nature, and a full account has not been published, they have been considered mainly to illustrate what would be the effect on the solar-constant value of changes in the shape of the spectral-irradiance curve, and to point out that future work may eventually lead to a further small revision in the solar constant. Gates *et al*'s preliminary results indicate that the solar spectral-irradiance curve is higher in the region 1.2 to 2.2 μ than indicated by the Smithsonian Institution, and coincides with that from a 7000K black-body sun over the spectral range 1.5 to 1.8 μ. This amounts to an increase of about 0.07 cal cm^{-2} min^{-1} above the Smithsonian data. It must be emphasized that this would not result in an increase of 0.07 cal cm^{-2} min^{-1} in the solar constant. As explained earlier, assumption that the Smithsonian spectral-irradiance curve is too low in the infrared would cause its value of the solar constant to be a little high rather than low. The effect of the change suggested by Gates *et al*'s data can easily be estimated. Since the change is within the spectral range of the Smithsonian spectrobolometer, an infrared increase of 0.07 cal cm^{-2} min^{-1} would have to be compensated for by a decrease in the spectrobolometer curves elsewhere in the spectrum, so as to keep the entire curve normalized to the pyrheliometer reading. If the decrease were spread uniformly over the visible and ultraviolet, it would be approximately 6 per cent. After extrapolation to zero air mass, the area under the visible and ultraviolet portion of the spectral-irradiance curve would be deficient by about 0.08 cal cm^{-2} min^{-1}, whereas the excess in infrared would remain near 0.07 cal cm^{-2} min^{-1}. Thus, the effect of adopting such a change as that suggested by Gates *et al* would be to lower the solar constant by about 0.01 cal cm^{-2} min^{-1} and to lower our visible and ultraviolet values by about 7 per cent.

In the ultraviolet, the spectral-irradiance curve adopted in the present work is slightly higher than the data used by the Smithsonian Institution, as shown in fig. 2. This change in shape introduces a small effect of the same nature as the example just presented, but tending to increase the solar constant. However, because the magnitude of the increase is only about 0.1 per cent, it has been neglected.

If we regard Gates *et al*'s data [20] as an outside limit to possible changes in the solar spectral-irradiance curves, it seems reasonable to suggest that uncertainties in the shape of the solar spectral-irradiance curve introduce into the solar constant an uncertainty no greater than 0.01 cal cm^{-2} min^{-1}, or 0.5 per cent. It appears unlikely that the ultraviolet *zero air-mass correction* can be changed by as much as 10 per cent of its present value, or 0.009 cal cm^{-2} min^{-1}. The infrared *zero air-mass correction* is probably subject to even less uncertainty. It seems improbable that it can be changed from 0.076 by more than 0.005 cal cm^{-2} min^{-1}. Thus, the uncertainty introduced into the solar constant by the ultraviolet and infrared *zero air-mass corrections* does not exceed 0.014 cal cm^{-2} min^{-1}, or 0.7 per cent. Uncertainties in the ultraviolet and infrared *spectrobologram corrections* do not appear to be large enough to introduce a possible error of more than 0.5 per cent in the solar constant.

To the uncertainty contributed by the ultraviolet and infrared corrections, and by the shape of the solar spectral-irradiance curves, must be added any uncertainty in the Smithsonian scale of pyrheliometry. The accuracy claimed is of the order of a few tenths per cent, but the magnitudes of the changes made in 1932 and 1952 (respectively, 2.4 and 1.8 per cent) seem to indicate a somewhat greater uncertainty. It would appear reasonable to suggest that the probable error in the solar constant is 2 per cent, and thus that the best value of the solar constant is 2.00 ± 0.04 cal cm^{-2} min^{-1}.

Although the spectrum of the sun below 2000Å is still little known, the total energy involved, even assuming that large variations may occur, is small and its contribution to the solar constant is negligible. For example, a 5000K black-body sun being assumed, which is probably more intense than the actual sun below 2000Å, the energy from 2000Å to 1500Å is only 0.03 per cent of the solar constant, and is 98 per cent of the energy in the entire spectrum below 2000Å. Further, the energy in the first line of the Lyman series of hydrogen, at 1216Å, has been found [21] to be of the order of 0.1 erg cm^{-2} sec^{-1}, or 10^{-7} of the solar constant. Also, the total energy in the X-ray spectrum was estimated by Byram *et al* [22], from measurements with photon counters, to be of the order of 1 erg cm^{-2} sec^{-1}, or 10^{-6} of the solar constant.

9. Earlier revisions of the solar constant

It may be appropriate at this point to make brief mention of a number of more recent attempts to revise the corrections and solar-constant values of the Smithsonian Institution. Schatzman [23], erroneously assuming that the Smithsonian ultraviolet *zero air-mass correction* is based upon the assumption of a 6000K black-body, has stated that the Smithsonian solar-constant value should be reduced by 2.44 per cent to agree with the preliminary rocket results. Allen [24] has pointed out Schatzman's error, and at the same time has proposed an increase of 0.06 cal cm^{-2} min^{-1} in the Smithsonian solar-constant value to allow for infrared energy beyond 2.4 μ. Nicolet [25; 26] has shown that Allen failed to subtract the Smithsonian infrared *zero air-mass correction* before adding his own. Nicolet went on to synthesize a zero air-mass solar spectral-irradiance curve from the preliminary rocket data and astrophysical theory, and has normalized his resulting curve using Smithsonian data. However, he misinterpreted the changes in scale and the *zero air-mass corrections* applied by the Smithsonian Institution in such a way that his results are essentially presented in terms of the scale used by the Smithsonian Institution leading to their solar-constant value of 1.946 cal cm^{-2} min^{-1}, and in which a scale error is indicated. Georgi [27] pointed out that Nicolet's results include a scale error, and revised them accordingly. Houghton [28] and Fritz [29], using preliminary results of solar ultraviolet spectra obtained during rocket flights and new estimates for the infrared end of the solar spectral-irradiance curve, obtained values for the solar constant, which, like Georgi's, are free from errors in interpretation of the Smithsonian data. However, Houghton, Fritz, and Georgi all failed to show that the ultraviolet and infrared extensions which they applied to the observed Smithsonian solar spectral-irradiance curve were consistent with the ultraviolet and infrared *spectrobologram corrections* actually used by the Smithsonian Institution. Also, their results must be increased by 1.8 per cent in agreement with the change in scale announced by the Smithsonian Institution in 1952.

The last revision by the Smithsonian Institution [6; 8] of the ultraviolet and infrared corrections was in 1927. At that time, and since then, it has answered criticism of the magnitude of the infrared and ultraviolet corrections which it applies in its work with the statement that, owing to its procedure of normalizing the spectrobolograms according to the pyrheliometer reading, the magnitude of these corrections is unimportant because any errors are largely self-compensating. Although this may happen in special cases, it is easy to show that it does not hold in general. For example, if its *spectrobologram corrections* are too small the spectrobolograms when normalized and extrapolated to zero air mass are too high, and give too great a value for the zero air-mass irradiance in the spectral interval 0.346 to 2.4 μ; then, if the *zero air-mass corrections* which are added are also too small, some degree of compensation results, and the solar-constant value might be nearly correct. It is possible to postulate conditions such that a compensation of this type would indeed occur, and it happens that the Smithsonian has, in fact, adopted ultraviolet and infrared corrections which vary with air mass and water vapor in such a way that the solar constant is not greatly changed from the value that would be obtained if the ctions were assumed to be zero. It also follows f its corrections are all multiplied by a constant , the resulting solar-constant value will still not greatly changed from the value which it obtained. For example, application of zero ultraviolet and infrared corrections would result in a value near 1.92 cal cm^{-2} min^{-1} for the zero air-mass irradiance between 0.346 and 2.4 μ, instead of the value 1.835 cal cm^{-2} min^{-1} which is obtained with the corrections now used, and the solar constant of 1.92 cal cm^{-2} min^{-1} which would result is not much different from the value 1.934 cal cm^{-2} min^{-1} which the Smithsonian Institution now gives. However, self-compensation cannot, in general, be expected to occur. The fact that the relations between the Smithsonian *spectrobologram corrections* and *zero air-mass corrections* happened to be such that this compensation appeared to occur is not fundamental evidence that compensation really does occur. Adoption of a change in the *zero air-mass corrections*, with no change in the *spectrobologram corrections*, or *vice versa*, will affect the solar constant and no compensation will occur to prevent this.

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